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Reconstructing thermocline hydrography using planktonic foraminiferal Mg/Ca: Implications for paleo-ENSO during the Holocene

Andrew Olland Parker
University of Colorado Boulder

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**Reconstructing thermocline hydrography using planktonic foraminiferal
Mg/Ca: Implications for paleo-ENSO during the Holocene**

By

Andrew Olland Parker

Submitted in fulfillment of departmental honors and partial fulfillment of

Bachelors of Arts

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Department of Geological Sciences

at the

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April, 2011

Reconstructing thermocline hydrography using planktonic foraminiferal Mg/Ca: Implications for paleo-ENSO during the Holocene

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Abstract

Interannual variations in thermocline hydrography of the eastern tropical Pacific are today dominated by the El Niño/Southern Oscillation (ENSO). Mixed layer thickness, thermocline depth, and sea surface temperatures all decrease under La Niña conditions. Changes in these parameters are responsible for oceanographic and climate anomalies that have far reaching effects. Understanding how water column stratification of the eastern tropical Pacific has changed over time can lend insight into the past dynamics of ENSO, yet this is a poorly constrained area of study.

We present a record of upper water column stratification history during the Holocene, using core PC14 from the Soledad Basin, Baja California (25.2N, 112.7W). We use Mg/Ca differences between *G. bulloides*, and *N. pachyderma* (d.) to reconstruct changes in the vertical stratification. *G. bulloides* reflects the upper most surface conditions during peak spring upwelling. *N. pachyderma* (d.) favors conditions near the bottom of the thermocline consistent with previous studies that it follows the Deep Chlorophyll Maximum (DCM). We apply this multi-species approach to test the hypothesis, based on *G. bulloides* Mg/Ca, that the early to middle Holocene was characterized by millennial-scale oscillations in ENSO mean state. Understanding the behavior of ENSO over long timescales can provide a path to evaluating the potential of orbital and solar forcing of ENSO dynamics.

Thesis Supervisor: Dr. Thomas M. Marchitto, Jr., Associate Professor, CU-Boulder

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I also would like to thank the entire Paleooceanography research group. Our paper readings and Friday get togethers have greatly contributed to my academic development. I thank the faculty of the Geological Sciences department, in particular, Kevin Mahan, Becky Flowers, Scott Lehman and Alexis Templeton. They have shown me how much fun learning can be, and have been great mentors as well as friends during my years at CU. They have shown me that, hard work beats talent when talent doesn't work hard. I have seen that hard work will get anyone anywhere. When I look back at this thesis 10, 15, 20 years from now, I will know that where I am then, is because of where I was today.

I thank my family whom from a young age instilled the importance of school and life-long learning with me. They have supported every decision I have ever made. They have shown me how to be strong, and persevere through the difficult times. I have learned through them that everything happens for a reason, and without them, I would never be where I am today.

And lastly, to my beautiful fiancé Megan, Thank You. Thank you for always being interested in my research. Thank you for being an ear when I needed to vent. I thank her for her support and love that has been unconditional since the day we met. Thank you for making me coffee in the morning after a long night, or rubbing my back after a long day of picking. I am so blessed to have someone like her that supports all of my ambitions and is willing to spend a lifetime with me learning, teaching and living.

Contents

ABSTRACT.....	3
ACKNOWLEDGMENTS.....	4
CHAPTER 1: INTRODUCTION.....	7
CHAPTER 2: BACKGROUND.....	12
2.1: Modern ENSO	
2.2: Paleo-ENSO during the Holocene	
2.3: Solar forcing of ENSO and the “Ocean Dynamical Thermostat”	
CHAPTER 3: HYDROGRAPHY.....	27
3.1: Oceanographic setting	
3.2: Foraminifera	
CHAPTER 4: METHODS.....	34
CHAPTER 5: DATA AND DISSCUSSION.....	35
CHAPTER 6: CONCLUSIONS.....	44
REFERENCES.....	47

CHAPTER 1: INTRODUCTION

The tendency for Earth's climate to change is the norm, not the exception. Global records of climate have shown that climate changes on the timescales of millions of years down to centuries and decades. Within the last century, increased levels of greenhouse gases such as CO₂ attributed to the burning of fossil fuels is believed to be driving global warming. Historically, fluctuations in non-anthropogenic atmospheric CO₂ appear concordant with changes in global temperature (figure 1). The fidelity between CO₂ and temperature anomaly is strong. We see that the last 800ka has been characterized by ca. 100ka oscillations in CO₂ that are synchronous with ca.100ka oscillations in temperature anomalies. The cold periods of these cycles (glacials) appear to last much longer than warmer periods (interglacials). While this glacial-interglacial variability appears to be controlled in large part by orbital scale forcings, they fail to provide an explanation for the why the most recent interglacial period, the Holocene, has been relatively stable since the Last Glacial Maximum (LGM).

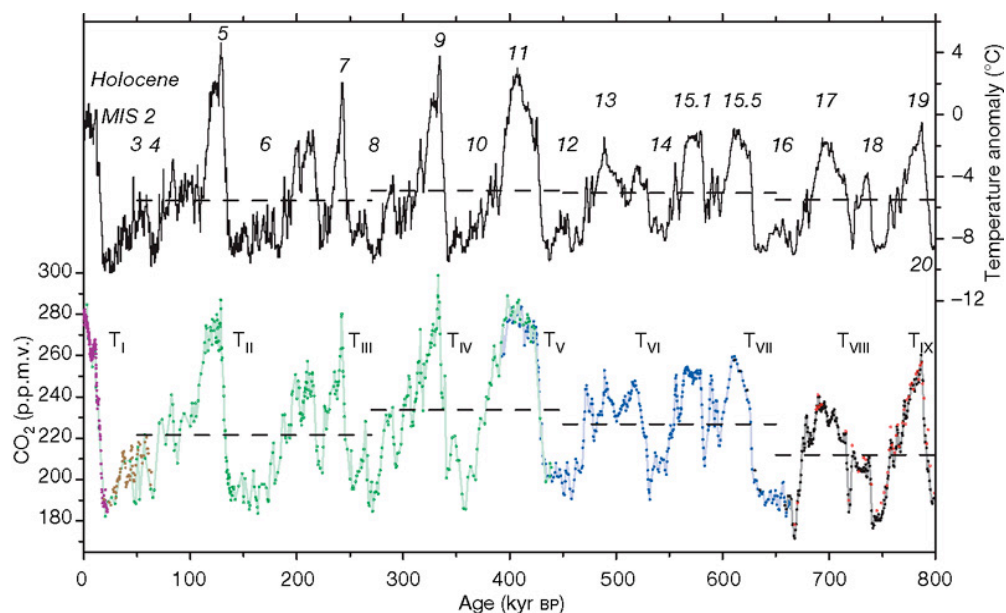


Figure 1: An 800ka record of CO₂ and temperature anomaly from EPICA Dome C, Antarctica. From Lüthi et al., 2008.

In figure 2 we see d¹⁸O from two major ice coring operations in Greenland. The orbital scale variability apparent in figure 1 is also present, superimposed on the entire record. At ~11ka, the end of the last glacial, the record becomes flat. Instead of diving into another glacial, the record becomes apparently very stability in the context of the respective time scale. However, the Holocene is not without it's fair share of variability. For example, Mayewski et al. 2004 analyzed nearly 50 globally distributed paleoclimate records and found evidence for as many as 6 periods of rapid climate change during the Holocene. The authors' note that variations documented in paleoclimate records of the Holocene, while smaller in amplitude from the larger variations that characterize the last glacial cycle, are larger and more frequent than previously thought. Significant, rapid variations occurred as quickly as a few hundred years and because modern Humans were around at this

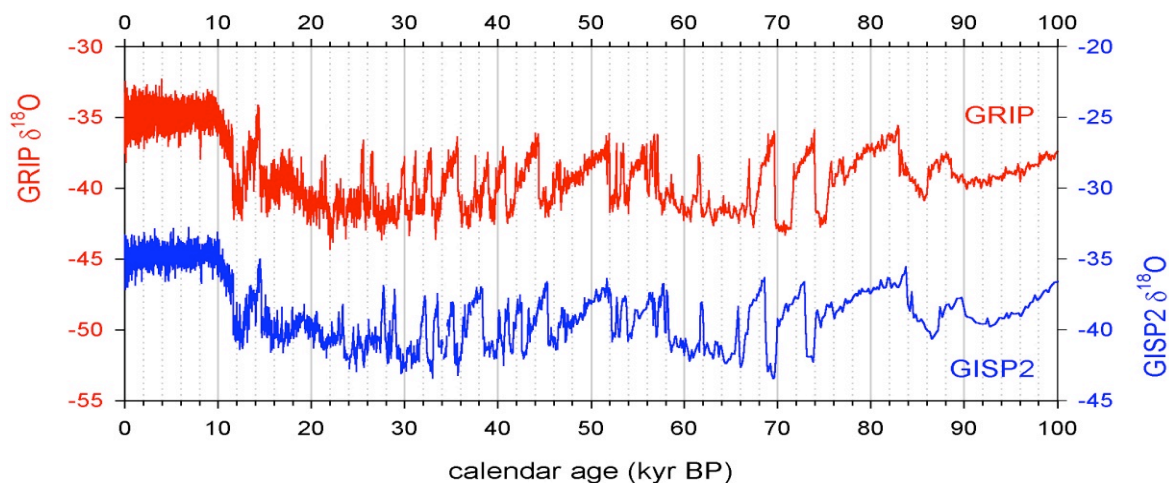


Figure 2: Oxygen isotope data from the Greenland Ice sheet of the last 100ka show significant variability in climate and are in high fidelity with the data from Antarctica in figure 1. From Dansgaard et al., 1993; Grootes et al., 1993.

time, studies have attempted to document the collapses of known societies with periods of rapid climate change. Hodell et al 2001 showed that the 1200-1000 cal yr B.P. rapid climate event of the late Holocene was synchronous with the downturn of the Mayan civilization. More recently, the beginning of the Little Ice Age forced the Vikings to abandon their establishments on Greenland around 600 cal yr B.P. (Buckland, et al. 1995, Mayewski et al. 2004). The potential effect climate change can have on a society is devastating. Recent observations of rapid climate change due to human activity have spurred a sense of urgency to understand how continued anthropogenic perturbations will affect the climate system, and humans in the future.

In order to properly understand the full extent of anthropogenic climate change, we must first better understand the natural variability. General Circulation Models (GCM's) are considered a leading tool in making predictions of future climate, yet these models often leave out critical aspects of the climate system due to a lack of information. Improving modeling capabilities will rely on the continued improved understanding of the role each physical climate process has in the regulation of global climate. This is achieved by evaluating the processes' present day dynamics as well as prior tendencies. The challenge however, is the incredible complexity that is the climate system. Working in accord with each other, the sun, oceans, atmosphere and ecology all have critical roles when it comes to climate

regulation. Every process seems to be intricately interconnected thus focusing on specific relationships is often the best method to approach.

One of these couplings, the ocean-atmosphere system, is of particular importance especially when one considers the fact that the oceans cover more than 70% of the global surface, have a heat capacity nearly 30 times larger than the atmosphere, and is the largest, fastest exchanging reservoir of carbon (Stocker, 2000). Early studies of how the ocean interacts with the atmosphere highlighted the stabilizing effect the oceans have on year-to-year climate variations, particularly when the climates of coastal and interior locations along the same latitude are compared. (Weyl, 1968). The recognition of the importance atmospheric-oceanic systems have in regulating climate on a year to year basis, as well as multi-decadal timescales has only been known for a short time. Phenomena such as the Arctic Oscillation (AO), North Atlantic Oscillation (NAO) and the El-Niño/Southern Oscillation (ENSO) have shown in recent times that atmospheric-oceanic coupled systems can have drastic effects on climate on an annual to interannual basis. Arguably to most importance of these is ENSO, which has been shown to produce global climate anomalies associated with it's end member phases (Salinger, 2005). As a result of this observation, considerable attention has been dedicated to investigating ENSO past history, as it could potentially help to explain Holocene climate variability.

This thesis will summarize the mechanisms of the ENSO system, explore prior studies of paleo-ENSO tendencies during the Holocene, discuss the potential solar influence on ENSO, as well as present multiple foraminiferal Mg/Ca records

from the Soledad Basin, Baja California; a region that exhibits a strong modern day relationship with ENSO. I will show that ENSO appears to respond to a millennial scale solar forcing of the tropical Pacific Ocean during the early to middle Holocene. While models have simulated the potential response of ENSO to solar forcing (dubbed the “ocean dynamical thermostat” to be discussed in chapter 2), no study prior to Marchitto et al. (2010) has demonstrated this relationship in sedimentary archives. Using a multi-foraminiferal approach to reconstruct thermocline hydrography, I will show that large, millennial scale changes in *G. bulloides* Mg/Ca are paralleled by *N. pachyderma* (*d.*)Mg/Ca records, reflecting changes in mean ENSO state. These oscillations are concordant with a millennial scale solar forcing of the tropical Pacific; implying that the “ocean dynamical thermostat” was an important mechanism in regulating tropical Pacific sea-surface temperatures (SST) during the Holocene.

CHAPTER 2: BACKGROUND

The importances of atmospheric-ocean interactions in regulating global climates are well known. Systems such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) have large regional weather implications, particularly for Europe and Siberia. The El-Niño/Southern Oscillation (ENSO) however, is the leading phenomena responsible climate anomalies on an annual-interannual basis felt globally (Rosenthal and Broccoli, 2004). ENSO has been held responsible for everything from droughts and forest fires the Indo-Pacific to flooding and fishery loss off the Peru and Ecuadorian coasts and may even influence other systems such as the NAO and AO. These anomalies stress communities financially and socially. Recent strong ENSO events have place an increased significance for understanding the predictability of ENSO, so communities can better prepare in advance of expected weather events. ENSO expert Mark Cane points out in a 2005 paper that while there is a tendency to hold El Niño responsible for just about anything unusual climatically that happens anywhere, understanding the predictability of these events may lead to El Niño years may being the least costliest for communities (Cane, 2005). This is because the climatic events associated with El Niño are predicted up to a year in advance, allowing for preparations to be made. Cane uses the 1997-1998 El Niño as an example. Given the significant warming of the eastern tropical Pacific (ETP) that year, the city of Los Angeles cleared all storm drains in advance of anticipated heavy rains, preventing potential flooding hazards. The ability to predict ENSO phases will have significant implications for the way communities across the globe prepare for impending weather trends. However,

recent global warming maybe causing ENSO and it's associated climatic patterns to change. While there is a statistically strong association between weak Asian summer monsoons and El Niño events, we have seen recently this relationship to break down. During the 1997-1998 El Niño, monsoon strength remained nearly normal (Kumar et al. 1999). With increasing global temperatures and greenhouse gases comes the increasing uncertainty of how ENSO will act in the future. GCM's are a primary means of simulating how future climate situations will pan out, yet ENSO simulations are not their strong point in part because the physical parameters that drive ENSO behavior are still being worked out (Cane, 2005). For now, there remains no unification among GCM predictions of future ENSO as it relates to global warming. Current GCM predictions suggest little to no change in future ENSO, however, there is little confidence in that prediction. Continued research of present and past ENSO behavior is key to improving GCM predictions.

2.1: MODERN ENSO

The physical mechanisms of ENSO and associated SST patterns across the equatorial Pacific Ocean (EP) were first published by Jacob Bjerknes in 1969. Bjerknes provided the first description of normal and El Niño like SST patterns in the EP and associated them with specific atmospheric wind conditions. Since this work of Bjerknes, a widely accepted explanation for the ENSO system has been developed (Cane, 2005).

A La Niña state in the EP is characterized by SST's being 4-10°C cooler in the east versus the west (Figure 3). These features are noted as the eastern cold tongue and the western warm pool. In the eastern cold tongue, the thermocline is shallow

and steep, often no deeper than 50m to the top of the thermocline, which allows for cold waters to upwell creating the cold tongue. The upwelled waters are rich in nutrients, allowing for high productivity across the Central and South American coasts. These waters are major fisheries for the natives of this region. In the west, easterly surface winds pile up warm water. The western warm pool holds some of the ocean's warmest waters as the thermocline lies much deeper ($>100\text{m}$). Because of this, any upwelling in the warm pool is warmer than its eastern counterpart. The warm waters of the western warm pool cause the atmosphere above to also be relatively warm, and humid. As warm air rises, it cools, condenses and creates precipitation. During La Niña years, the monsoon is strong over the Indo-Pacific region; bring rain to northern Australia, Indonesia, Papua New Guinea and the rest of southeast Asia. The convective loop is completed in the east as air moves east aloft and descends over the high-pressure region set up by the cold tongue, lacking significant moisture. This east-west convective loop is called the Walker Circulation.

The SST pattern observed in the EP seems unexpected because the equatorial Pacific Ocean receives the same amount of isolation in the east as the west. So, why is it that such a strong SST gradient exists from east to west? The answer it turns out, involves both the ocean and the atmosphere in a positive feedback loop referred to as the Bjerknes feedback. (Sarachik and Cane, 2010). For La Niña, as easterly trade winds meet near the equator, Ekman transport deflects waters to the north of the equator to the right of the wind direction, and waters to the south of the equator to the left. The divergence of these water masses towards the poles must be replaced by water from below, inducing the equatorial upwelling that draws up the

thermocline and upwells the cooler waters to the surface in the east. As the trades continue across the EP, they pile water up in the west. This “pile” of water is much warmer than in the east, and the thermocline is forced deeper underneath the warm water. The winds set up an SST gradient that in turn causes the winds to strengthen. The easterlies blow because of pressure gradients set up by the SST pattern. In the east, cold waters produce high pressure while in the west, warmer waters produce low pressure. Because air flows from high to low pressure, the surface winds ride along the pressure gradient set up. Thus, the stronger the SST contrast is from east to west the stronger the winds will blow, producing stronger upwelling in the east and more piling up in the west, maintaining and/or strengthening the pressure gradient and completing the positive feedback scenario (Cane, 2005; Sarachik and Cane 2010).

The Bjerknes feedback works in the opposite way for El Niño (figure 4). Relaxed easterlies can be due to a weakening of the SST pattern across the EP. Weaker winds cause reduced upwelling, which forces the eastern thermocline to deepen as well, meaning any upwelling is warmer than during La Niña phases, further reducing the SST gradient. This reduction in upwelling strength not only means warmer waters are upwelled, but also that the waters are less rich in nutrients. The loss of nutrient to these waters causes a collapse of the fisheries as fish are forced to migrate away in the search for a sufficient food supply. The relaxed winds also mean less piling up of water in the west. As a result, western warm pool waters surge east, further contributing to the warming of the eastern Pacific. The eastward migration of western warm pool takes the Indo-Pacific

atmospheric convection with it. The rainforests begin to dry out leading to massive wild fires. These fires are so severe that El Niño years are often years of increased rates of CO₂ accumulation in the atmosphere (Sarmiento and Gruber, 2002).

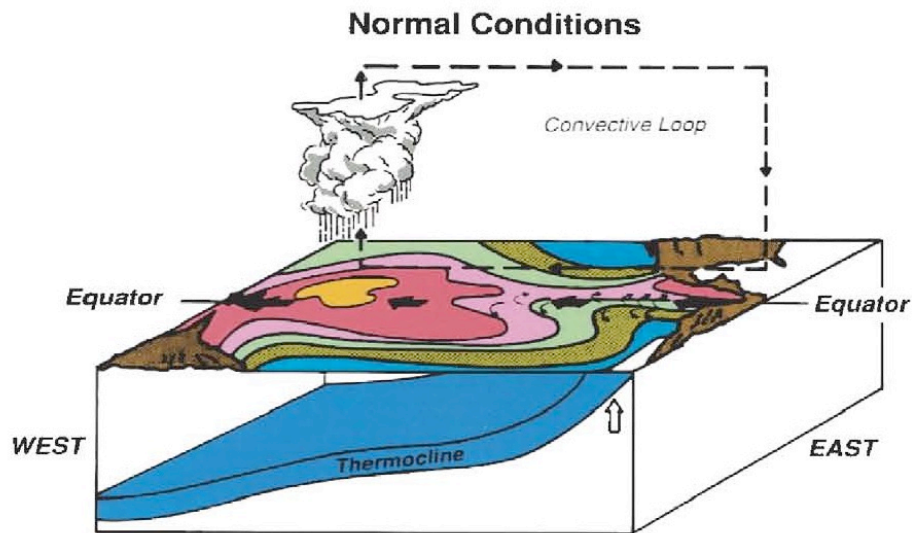


Figure 3: From Cane, 2005. Schematic illustration of Normal or La Niña conditions across the equatorial Pacific Ocean. In the east the thermocline is steep, and shallowing bringing cold water to the surface while in the west, the waters are warm and thermocline is deep. Convection lies over the Indo-Pacific. This condition is a result of strong easterly trades and SST gradient.

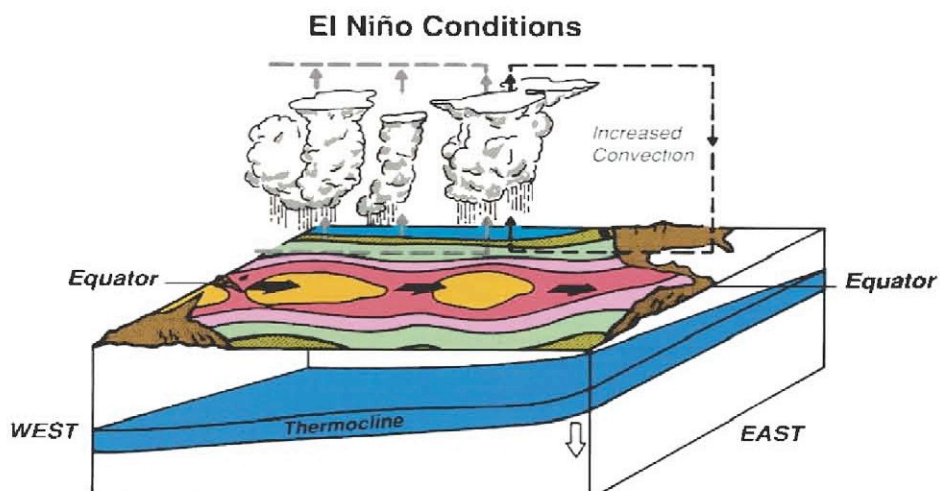


Figure 4: From Cane, 2005. Schematic diagram of El-Niño conditions in the equatorial Pacific Ocean. The cold tongue is not warm and easterlies are relaxed, as the SST gradient is not as strong as it is during La Niña. The monsoon rains push

east leaving the Indo-Pacific dry while bringing flooding rains to areas not prone to such conditions.

Today, there are numerous different ways of monitoring the state and strength of ENSO. The Southern Oscillation Index (SOI) is the atmospheric evaluation of ENSO that relates difference in sea-level pressure near Darwin, Australia to the sea-level pressure near Tahiti. It's oceanic counterpart, the Nino3 index, is a measurement of the SST anomaly between 90W-150W and 5S-5N. In figure 5, we see that the SOI and Nino3 indices mimic each other with high fidelity. The close

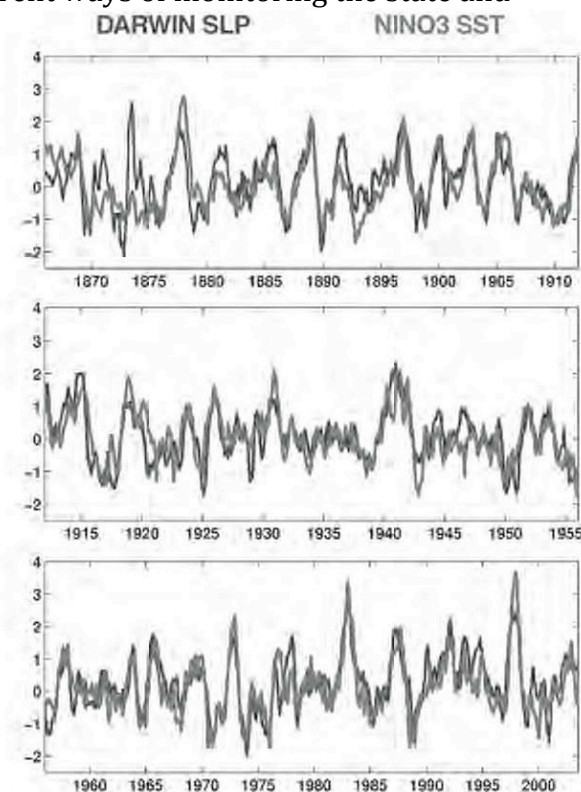


Figure 5: From cane 2005. The SOI and Nino3 plotted together for the last 130 years (instrumental record). The two records show a strong correlation with each other. Authors note the discrepancy early on is due to data quality problems.

similarity between each of the time series indicates that both indexes must be representing the same phenomena (Cane, 2005; Sarachik and Cane 2010). ENSO has a periodicity of 2-7 years. The periodicity arises as westerly winds send upwelling Rossby waves west and downwelling Kelvin waves east. When each wave reaches the boundaries of the EP after travel times on the scale of months, they are reflected back along the equator. These oscillating cold and warm signals interact with the Bjerknes feedback at longer (interannual) timescales. Dubbed the “delayed oscillator” this mechanism is responsible for the periodicity of each phase of ENSO. While understanding modern ENSO dynamics and monitoring phase changes are

done with relative ease in the instrumental world, understanding the behavior of ENSO in the past may in fact be the key to understanding the future.

2.2: PALEO-ENSO DURING THE HOLOCENE

Records of ENSO in the paleoclimate record exist as far back as 130ka (Hughen et al 1999). For example, during the Pliocene it has been hypothesized by Philander and Federov (2003) as well as Federov et al. (2006) that an overall warmer climate led to the thermocline being deeper everywhere, preventing colder waters to upwell and thus the EP was in a constant El Niño like state. These studies also hypothesize that the demise of El Niño could have led to the onset of glaciations in the Northern Hemisphere. Much more focus over the last two decades has been placed at studying ENSO in the Holocene (10ka to present) for two reasons, (1) records are of higher resolution and (2) many substrates used to make reconstruction i.e. corals, varves etc. typically only date back a few thousand years. While there has been an explosion of paleo-ENSO records produced recently, a unified theory has yet to emerge as studies continue to produce conflicting results.

Generally, it is accepted that during the early to middle Holocene, ENSO was suppressed to a more La Niña like state. Foraminifera records suggest that during this time period the mean state of ENSO was more La Niña like (Koutavas et al. 2002; Rosenthal and Broccoli, 2004; Koutavas et al. 2006). By saying the EP was in a more La Niña like state is not to say El Niño was completely lost, but rather the majority of ENSO events were La Niña in character. Koutavas et al. 2002 used *sacculifer* and *G. ruber* to evaluate SST gradients using Mg/Ca and found that indeed the state of ENSO appeared to be depressed during the early and middle Holocene.

In fidelity with this study, Koutavas et al. (2006) used individual Mg/Ca of *G. ruber* to evaluate the SST gradient in the EP during the Holocene. They found that during the last glacial maximum (LGM) a wider range of Mg/Ca recorded by *G. ruber* was a result of relaxed SST gradients and warmer conditions in the EEP. By the early and middle Holocene, small ranges in Mg/Ca suggest a more La Niña like state had emerged.

Moy et al. (2002) used laminated lake varves from Ecuador to construct a paleo-ENSO record. The way this proxy functioned is such that clastic sediment gets washed into the lake during heavy rains from El Niño. These sediments appear darker than the normal sediments in the lake so a count of the darker bands produces a frequency record of El Niño. The Moy et al (2002) record suggests that El Niño during the early Holocene may have been absent until 5000 BP when the dark varves begin to show up. This observation is also consistent with the observations of Tudhope et al. (2001) that the few El Niño events that occurred during the early Holocene were weaker than today's El Niño event and thus were not able to wash the clastic sediments into the lake. The increase in El Niño during the late Holocene is observed by Corregge et al. (2000) which found long lasting La Niña events begin to get interrupted by El Niño in the middle Holocene. Using corals from the heartland of ENSO, Vanuatu, the study found evidence for El Niño beginning in the later half of the Holocene.

Martinez et al. (2003) argues against a more La Niña like state during the early Holocene using foraminifera along with Leduc et al. (2009) who used individual *N. dutertrei* the same way Koutavas did with *G. ruber*, however the results

were not the same. Leduc found little to no change in oxygen isotope variations during the Holocene and suggested that there was little difference from the ENSO system of today. However, studies have shown that *N. dutertrei* in the EP prefers a habitat in the middle thermocline possible associate with a specific isotherm. Thus, any vertical migration of this isotherm would cause *N. dutertrei* to migrate with it, mitigating any potential temperature variations it may record due to a fluctuating thermocline in response to ENSO (Fairbanks and Wiebe, 1980; Fairbanks et al. 1982; Field, 2004). The ideal foraminifera would have a stable depth of habitat so it records the temperature changes felt in the water column due to ENSO. Even as uncertainty about the past behavior of ENSO exists, the evidence for a more La Niña like EP during the early Holocene appears to be the most agreeable observations in the great paleo-ENSO debate. Why then, was ENSO in a suppressed state during the early Holocene?

2.3: SOLAR FORCING OF ENSO AND THE “OCEAN DYNAMICAL THERMOSTAT”

We now know that natural variations in earth’s orbit, called Milankovich cycles, affect the amount of solar isolation the Earth receives from the sun. Over long time periods (great than 10ka), the reduced (or increased) amount of solar isolation caused by Milankovich cycles can either induce (or break) a glacial cycle. Clearly, the sun plays a critical role in regulating earth’s climate. But could the amount of solar isolation really affect ENSO behavior? In 1996 Amy Clement et al. published their modeling experiment findings of a possible solar control on the ENSO system. Dubbed the “ocean dynamical thermostat”, their paper proposed a mechanism thought which ENSO responded to an orbital forcing as a negative feedback,

mitigating any change the climate system might feel from such a perturbation. They state “An imposed heating induces greater equatorial upwelling that cools the equatorial SST. Meridional advection spreads the upwelled water off the equator leading to a basin average temperature change that is less than expected”. This is due to the response of the Bjerknes feedback to a warming or cooling: increased solar isolation in the tropics in particular, would cause the warmer west to heat faster than the cooler east, thus increasing the SST gradient across the EP. This stronger SST gradient would increase the east-west pressure gradient increasing the easterly trades and inducing more cold water to upwell. The meridional advection of the cold water allows for this feedback to be felt across the entire basin rather than just along the equator and thus this response would be referred to as La Niña-like. The ocean dynamical thermostat works in the opposite sense for a reduction in solar isolation, helping to keep the EP warmer. If ENSO is particularly sensitive to solar forcing it can explain the orbital-scale trend seen in paleo-ENSO records during the early-mid Holocene of a more La Niña mean state (see section 2.2 for references and discussion) because the ocean dynamical thermostat is most sensitive to summer-fall insolation which peaked during this time interval. In this sense, the ENSO system acts as a natural mechanism of the climate system in response to orbital or solar forcing and may help to explain why high latitude temperature changes are greater than tropical changes.

Since the inception of the ocean dynamical thermostat, many more studies have attempted to recreate this solar forcing of ENSO response (Cane et al. 1997; Clement et al. 1999; Mann et al. 2005, Emile-Geay et al. 2007 and Marchitto et al.

2010). Mann et al. (2005) investigated the response of ENSO to solar forcing changes over the last 1000 years with success. Mann et al. simulated the expected response of La-Niña to solar maxima during the Medieval Warm Period, and El Niño during solar minima during the Little Ice Age (figure 6). The study suggested that the ocean dynamical thermostat may have played a critical role in regulating Holocene climate. To further this observation, Emile-Geay et al. (2007) used the Zebiak-Cane model (used by both Clement et al. 1996 and Mann et al. 2005 too) to simulate a more La-Niña like state during the early and middle Holocene giving way to a more El Niño like parameter later in the Holocene. Their study recreated results with both solar and orbital scale variations during the Holocene (figure 7). It also simulated a millennial scale oscillation in ENSO specifically associated with solar forcing.

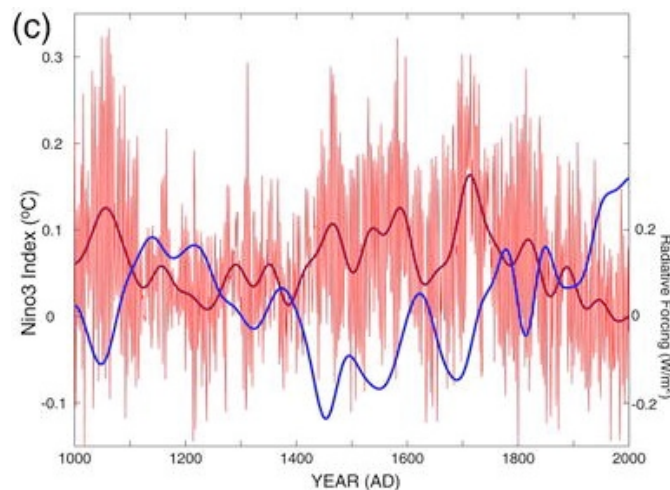


Figure 6: From Mann et al. 2005. Simulated response of ENSO to solar forcing during the last 1000 years. The blue line is the solar forcing while red represents the response of ENSO. 1000-1400 corresponds to an increased solar forcing and La-Niña like response while during the little ice age 1400-1850 solar minima is countered by El Niño.

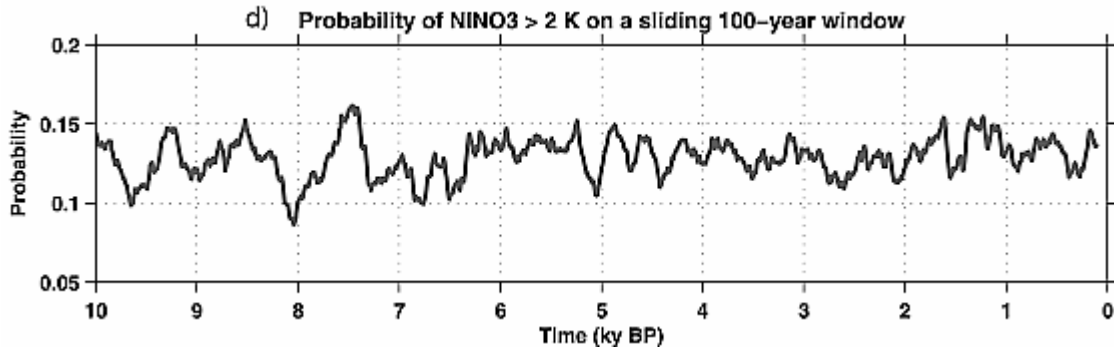


Figure 7: From Emile-Geay et al. 2007. Simulated response of ENSO through the entire Holocene and detrended for orbital variations. High probability represents great chance of El Niño. Millennial scale oscillations in ENSO are a result of solar forcing.

Marchitto et al. (2010) used *G. bulloides* Mg/Ca to reconstruct temperature variations off of Baja California, an area well connected to ENSO. Mg/Ca SST's were coldest during the early Holocene consistent with studies discussed earlier in this section. The *G. bulloides* record also reveals five millennial scale oscillations in SST during the early Holocene between 7 and 11.5 kyr. Marchitto et al. went on to compare the SST record with cosmogenic nuclide proxies for solar variations and found that the millennial scale oscillations in SST co-vary with millennial scale oscillations in cosmogenic nuclide proxies in a way consistent with the ocean dynamical thermostat (figure 8). Cosmogenic nuclide proxies ^{10}Be and ^{14}C are produced in the atmosphere by cosmic rays. When the sun is stronger, its magnetic field is also stronger, shielding earth from more cosmic rays than during times when the sun is weaker. This reduction in the amount of cosmic rays entering the atmosphere decreases the production of ^{10}Be and ^{14}C . In figure 8 we see that between 7 and 11.5 ka minimums in ^{10}Be and ^{14}C correspond to minimums in *G. bulloides* Mg/Ca (and thus SST). These minimums, indicating a stronger sun, is

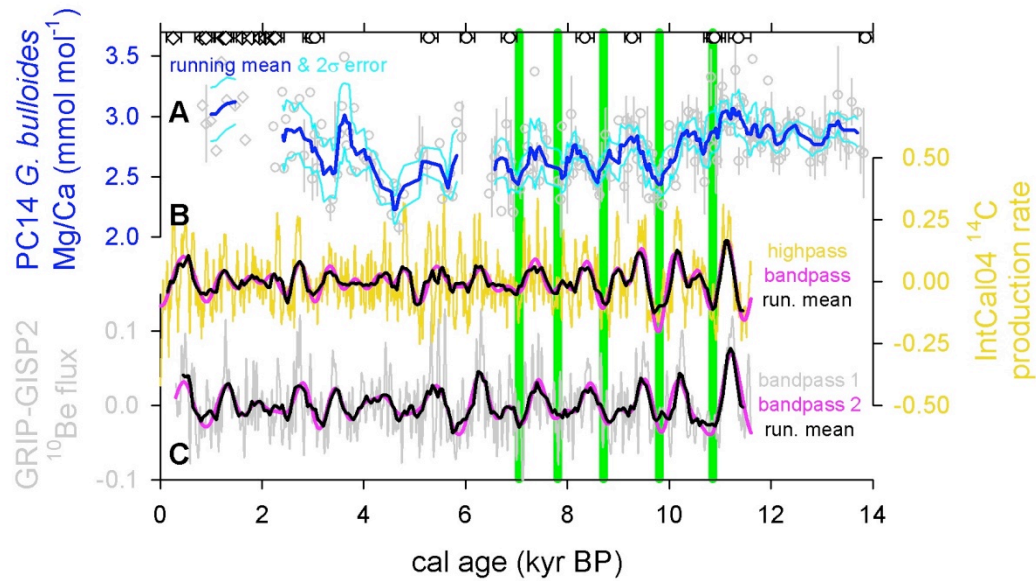


Figure 8: From Marchitto et al. 2010. *G. bulloides* Mg/Ca (Blue), ^{14}C (yellow) and ^{10}Be (purple) all display millennial scale oscillations between 7-11.5kyr. Minimums in Mg/Ca correspond to solar maximums indicative of an ocean dynamical thermostat response to an imposed warming.

consistent with the observation that a stronger sun would impose a heating of the EP inducing a more La Niña like state represented by cooler temperatures recorded by *G. bulloides*. Increased production in both ^{10}Be and ^{14}C are also synchronous with increase Mg/Ca of *G. bulloides*, indicative of reduced solar forcing and more El Niño like conditions in the EP. These observations agree with other proxies that are closely tied with ENSO teleconnections (figure 9). Highly coupled with the solar records (yellow and grey) as well as the *G. bulloides* (blue) are paleo-records of monsoon (light blue and green) as well as North Atlantic ice rafted Debris (IRD, red). During periods of positive solar activity when *G. bulloides* records cooler temperatures (La Niña like), both monsoon records indicate that a stronger monsoon was also operating in the western warm pool consistent with the Bjerknes feedback. North Atlantic IRD is believe to be connected to ENSO because during

periods of El Niño, wind patterns tend to shift in a way that would blow more IRD in to the North Atlantic. An alternative hypothesis is that during times when the North Atlantic is cooler, there is a great extent of sea ice. This increased sea ice cover not only enhances IRD, but as a result, also allows for a larger Scandinavian and Siberian ice sheets lowers the raising the albedo and causing less land heating which suppresses the monsoon (Morrill et al. 2003). The IRD record also appears to be synchronous with the solar, SST and ENSO proxies in figure 9, except around the 8.2ka event when it has been hypothesized that a large freshwater forcing from the melting Laurentide Ice Sheet greatly disrupted North Atlantic Ocean circulation (Barber et al. 1999).

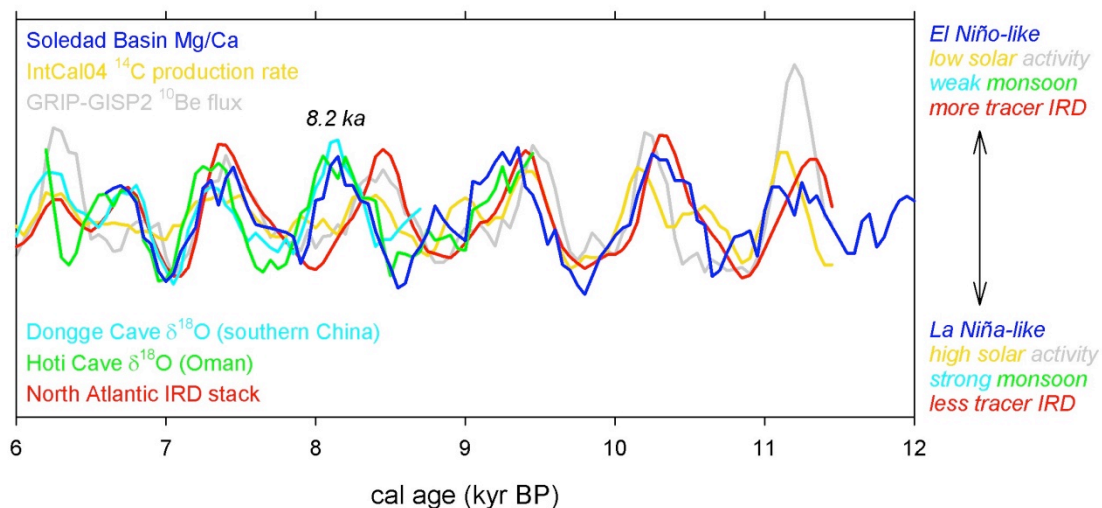


Figure 9: From Marchitto et al. 2010. Proxies for monsoon and IRD are also synchronous with cosmogenic nuclide proxy data and Soledad Basin Mg/Ca. *G. bulloides* (blue)(Marchitto et al. 2010), tree ring ^{14}C (yellow)(Reimer et al. 2004), ice core ^{10}Be (grey)(Finkel and Nishiizumi 1997, Vonmoos et al, 1006), Dongge Cave $\delta^{18}\text{O}$ stalagmite (light blue)(Wang et al 2005), Hoti Cave stalagmite $\delta^{18}\text{O}$ (green)(Neff et al 2001), and North Atlantic stack IRD petrologic tracers (red)(Bond et al. 2001) all appear in phase except at the 8.2 event.

If in fact solar isolation plays a significant role in the behavior of ENSO via the ocean dynamical thermostat, then this relationship has been underestimated in

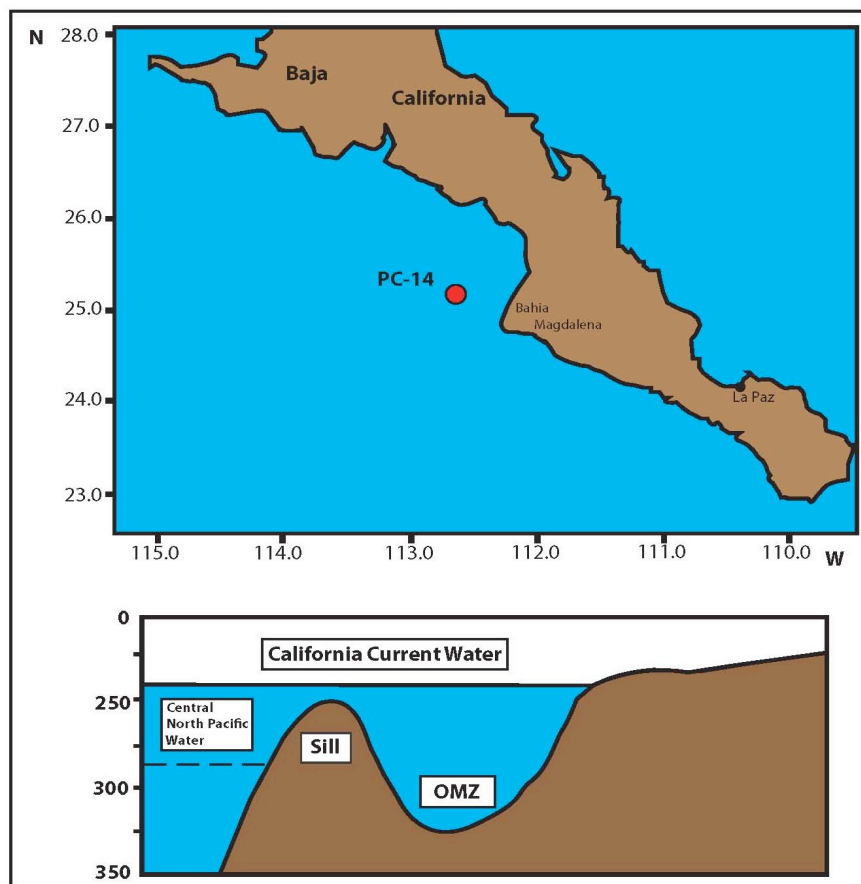
computer models reconstructions of past and future ENSO (Cane, 2005). The fidelity of the Mg/Ca, cosmogenic nuclide, and teleconnections proxies suggests that a millennial scale solar forcing did have a significant effect on the behavior of ENSO during the early to middle Holocene. However, *G. bulloides* is a near surface dwelling foraminifera, thus it's Mg/Ca record could represent SST variations that are not related to ENSO. For example, changes in local upwelling regimes in the Soledad Basin could be responsible for the observed Mg/Ca record. Changes in local upwelling would in turn affect the upper water column SST more than subsurface temperature. If changes in *G. bulloides* Mg/Ca are due to a regional large-scale change in the depth of the thermocline as expected under varying ENSO regimes, then we would expect deeper dwelling foraminifera variations in Mg/Ca that are both concurrent in time and similar in scale to the *G. bulloides* oscillations. Thus for this study, we analyzed the Mg/Ca the thermocline dwelling species *N. pachyderma* (dextral coiling) over the time span of 8.3-11.5kyr. When compared to *G. bulloides*, the Mg/Ca difference between these two foraminifera have been shown to closely monitor changes in the depth of the thermocline and associated thickness of the mixed layer (Pak and Kennett, 2002). We hypothesized that the variations in Mg/Ca of *N. pachyderma*(d.)would be similar in scale and parallel with the oscillations observed in *G. bulloides*, confirming the hypothesis that Mg/Ca variations of *G. bulloides* are the result from regional fluctuations of the thermocline corresponding to a solar forcing of ENSO.

CHAPTER 3: HYDROGRAPHY

3.1 OCEANOGRAPHIC SETTING

The core used for this study, MV99-GC41/PC-14, comes from the western coast of the Soledad Basin (25.2N, 112.7W) off Baja California; a region with strong teleconnections to ENSO (figure 10). The core was pulled from the bottom of the basin at depth of 540m, with an effective sill depth of 290m. PC-14 is

Figure 10: The Soledad Basin, Baja California. The shallow sill blocks the central north Pacific water from flowing in. The deep basin is anoxic allowing for low bioturbation and well preserved foraminifera.



coarsely laminated owing to low oxygen values (~ 5 mmol/kg) at the bottom of the basin, thus bioturbation is low. Preservation is great throughout. Foraminifera are robust and display glassy textures and spines often still intact. Based on 22 AMS radiocarbon dates, the core spans 13.9 kyr. High sedimentation rates in the basin of

~1m/kyr allow for good sample resolution of ~30 years. Marchitto et al. 2010 points out that while the resolution is not fine enough to pick up the 2-7 year periodicity of ENSO, it is sufficient enough to pick up any multi-centennial or millennial trends in ENSO.

The Soledad Basin modern SST patterns are highly tied to ENSO dynamics. The region is considered to be a transitional area where during years of strong El Niño, fresher and cooler waters of the California Current are blocked by the northward flowing saltier tropical surface waters (Fiedler and Talley, 2006; Kessler 2006). Significant variations in the surface layer hydrography of the EEP due to individual ENSO events have been documented by Durazo and Baumgartner, 2002, and Durazo, 2009, while variations in the surface layer hydrography over multiple ENSO events have been documented by Ando and McPhaden, 1997, and Castro et al. 2006. During periods of observed SST warming, studies document a deepening of the thermocline and a decrease in biological production. The upper water column sees changes in temperature due to the variability of the thermocline (figure 11). During the springtime when upwelling is at its strongest in the basin, SST minima range from 17°C during La-Niña years to 20°C during El-Niño years. For example, during the 2007 El Niño, waters at 50m depth were 2.5°C warmer than at the same time in 2008 (IMECOCAL data, G. Gaxilola). Over a 30 year period, SST anomalies in the Soledad Basin are highly correlated to the Niño3 index (figure 12) with 37% of monthly SST anomalies being explained by ENSO ($r=0.61$) compared to the local upwelling index which only explains 2% of monthly variance with a $r=-0.16$ (Figure 12).

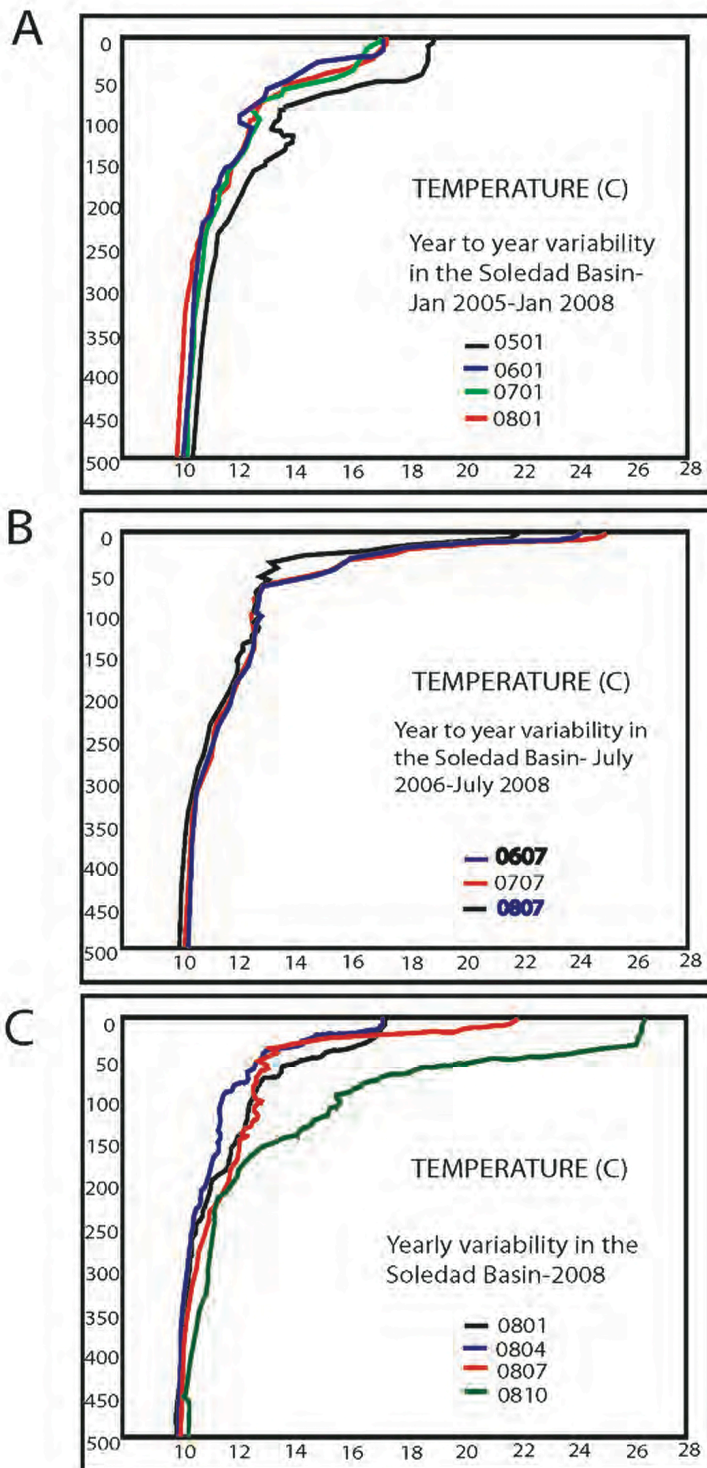


Figure 11: CTD data from IMECOCAL courtesy of Gilberto Gaxilola. Y-axis is depth while X-axis is temperature. (A) Interannual variability for January thermocline. (B) interannual variability for the month of July thermocline and (C) yearly variability during the El Nino year of 2008. Large variations are apparent between El Niño and La Niña years in (A). During the El Nino year of 2008, the thermocline progressively shallows out from January (black line in C) to October (green line in C). The 50m depth sees the largest variation in temperature.

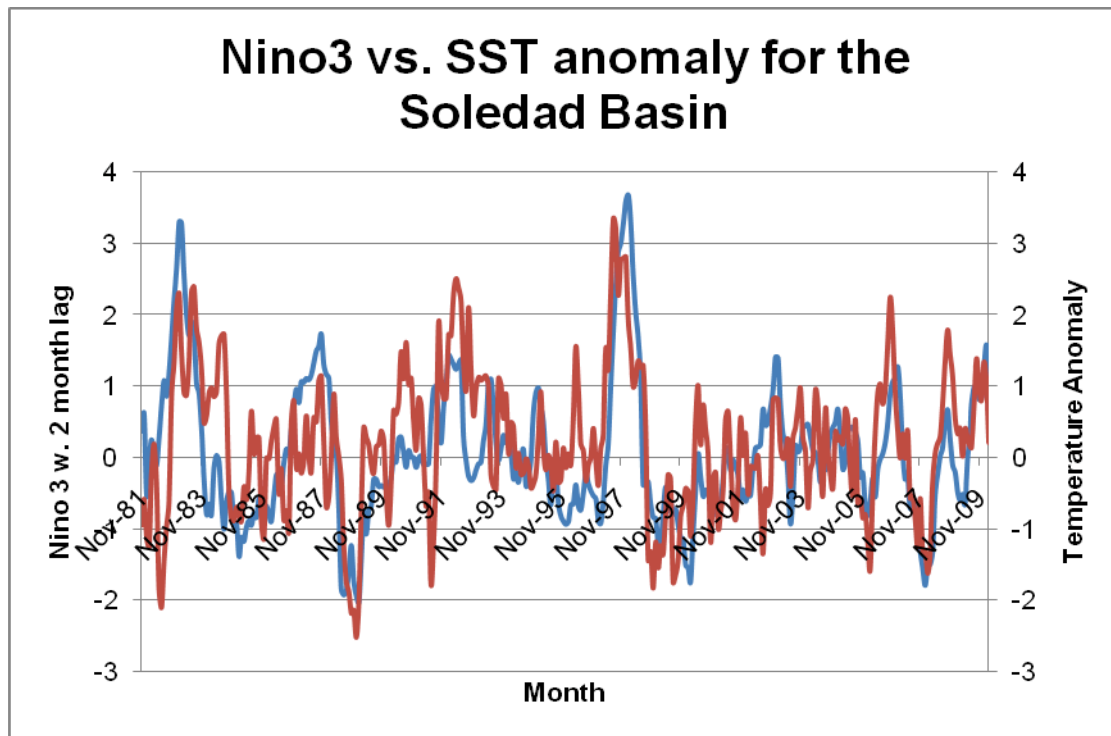


Figure 12: 30-year record of SST anomalies in the Soledad Basin taken by satellite observation. The changes in SST (red) nearly mimic the Niño3 index (blue). For the highest correlation, the Niño3 index is plotted with a two-month lag.

3.2: FORAMINIFERA

Applying a geochemical proxy for water temperature such as Mg/Ca to multiple planktonic species and taking the difference between them reflects the vertical ocean structure (Pak and Kennett, 2002). However, the accuracy in this method is dependent upon the ability to constrain each foraminifera's preferential depth of habitat. Factors controlling the depth of habitat include temperature, light and food availability; all which vary seasonally and inter-annual (Fairbanks and Wiebe, 1980; Fairbanks et al. 1982; Sautter and Thunell, 1991; Field, 2004). Thus, the successful application of this proxy relies on the understanding of modern day vertical distribution patterns of foraminifera in the field area.

Sediment trap studies are often the best indicators of vertical ocean structure, catching dead foraminifera as they fall through the water column while recording the environmental parameters at which they lived. Such studies conducted near the Soledad Basin region have classified *G. bulloides* as a near-surface dweller while *N. pachyderma* is regarded as a deep thermocline species (Sautter and Thunell, 1991; Patrick and Thunell, 1997; Wejnert et al. 2010). Other studies looking at the oxygen isotopic composition of the foraminifera's CaCO_3 places *G. bulloides* as a near surface dwelling species as well (Fairbanks et al. 1982; Ravelo and Fairbanks, 1992; Faul et al. 2000; Pak and Kennett, 2002; Field, 2004; Wejnert et al. 2010). Thunell and Sautter 1992, also note that *G. bulloides* maximum production occurs during the upwelling season while *N. pachyderma* usually occurs at a maximum during the pre-upwelling spring bloom.

N. pachyderma (d.) is a deep dwelling foraminifera that prefers cooler waters. There are two species, a left coiling (sinistral) and right coiling (dextral) variety. However, the left coil variety, while present in most ocean waters, almost always occurs in significant numbers in Polar Regions, as it prefers the coldest waters. Careful consideration was given during picking to ensure no left coiling species were included in each sample. The right coiling species used in this study has a habitat that is very closely tied with the Deep Chlorophyll Maximum (DCM) (Fairbanks et al. 1982; Sautter and Thunell, 1991; Pak and Kennett, 2002; Field, 2004). The DCM provides an ample food source for the species far removed from the surface. Modern fluorescence data from the Soledad Basin shows that vertical migration of the DCM through the water column is minimal, holding at a stable

depth independent of the water column's thermal structure at 50m (IMECOCAL data, G. Gaxiola). Thus, we can say with some confidence that the paleo-temperatures recorded by *N. pachyderma* (d.) are reflective of changes in the vertical migration of the thermocline through the DCM and not changes in temperature due to the vertical migration of *N. pachyderma* (d.) itself (figure 13,14). If the *N. pachyderma* (d.) data is tracking temperature changes due to variations in the thermocline related to ENSO, then the expected pattern should be synchronous with, and similar in magnitude to that of the changes recorded by the *G. bulloides* data (figure 14).

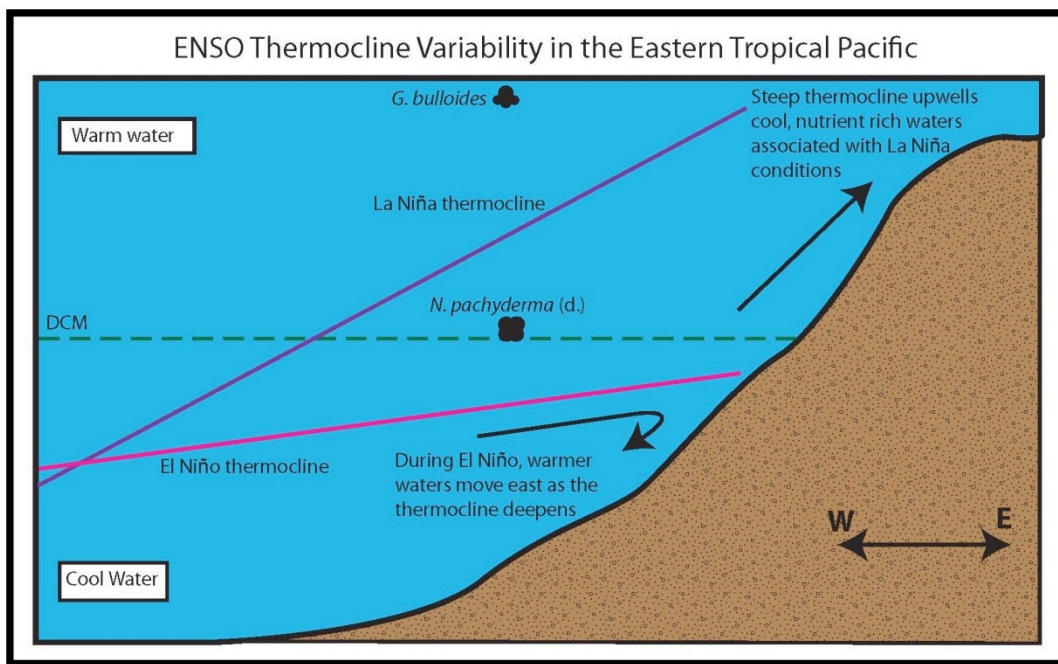


Figure 13: Schematic diagram of the vertical distribution pattern between *G. bulloides* and *N. pachyderma* (d.). Changes in temperature recorded by *N. pachyderma* (d.) are reflective of changes in thermocline structure as it passes through the stable DCM habitat. During an El Niño year the thermocline is deeper (red line) resulting in warmer waters both at the depth of the DCM and at the surface. During La Niña the thermocline is shallower (purple line), leading to cooling at both depths.

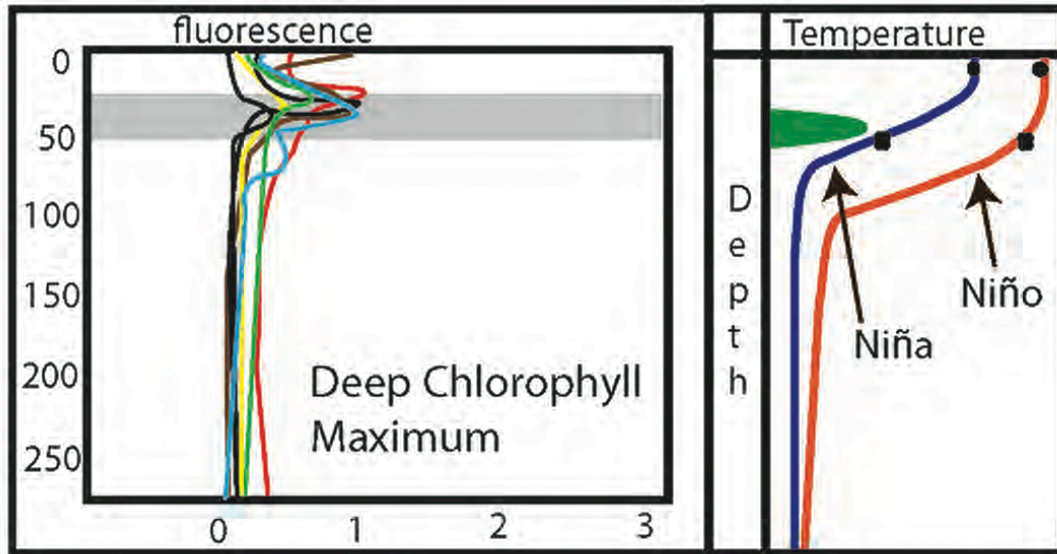


Figure 14: Left, selected IMECOCAL fluorescence data profiles of the DCM (courtesy of Gilberto Gaxilola) taken between 2005 and 2008. Fluorescence spikes around 45m indicate the deep chlorophyll maximum and the assumed preferred habitat of *N. pachyderma* (*d.*). The grey box indicates the minimum and maximum vertical extent of fluorescence peaks showing little vertical migration of the DCM. Right, schematic temperature profile illustrating the difference in ENSO thermoclines. Each foraminifera (bottom black dots are *N. pachyderma* (*d.*) and upper black dots are *G. bulloides*) sees a change in temperature similar in magnitude to the other. Therefore the *N. pachyderma* (*d.*) data should show similar changes in temperature as *G. bulloides* if forced by ENSO.

CHAPTER 4: METHODS

The age model for core PC-14 is based on 23 accelerator mass spectrometry radiocarbon dates on mixed planktonic (20) and mixed benthic (3) foraminifera (Marchitto et al. 2010). Sample resolution is spaced out at 5 cm intervals. 30 to 60 *N. pachyderma* (*d.*) were picked in the 155-250µm sieve size giving each sample an average of 30 to 60 month-long spring bloom snapshots. The sieve size was kept narrow to avoid any size-dependent influence on the Mg/Ca measurement. The 5cm sample resolution translates into ~30 year intervals, not short enough to resolve the ENSO periodicity but sufficient to resolve century and millennial scale trends in the mean ENSO state. Enough foraminifera were picked when available for replication of measurements to lower the error bar. Replicate samples were split and all samples were crushed between 2 glass slides under a microscope in a class 1000 clean room to open each chamber of the foraminifera test. Each sample was then cleaned reductively and oxidatively with anhydrous hydrazine and hydrogen peroxide, respectively, according to the procedures of Boyle and Keigwin (1985/86) and modified by Boyle and Rosenthal (1996). Large samples were then leached in weak acid for further cleaning. Upon cleaning, the samples were analyzed for Mg/Ca on a single collector Thermo-Finnigan Element-2 Inductively-Coupled Plasma Mass Spectrometer using the methods of Rosenthal et al. (1999) and modified by Marchitto (2005).

CHAPTER 5: DATA AND DISCUSSION

A total of 97 samples were analyzed between the time interval of 8.31 to 11.5 kyr B.P. Replicates were not run for samples between 9.1 and 8.31 kyr B.P. due to time constraints, however most data points beyond 9.1 do have replicates. Three samples fell well below the minimum size cutoff of 5 μg CaCO_3 (Marchitto, 2006), indicating that the material was most likely accidentally lost during the cleaning procedure. Three of the remaining 94 data points were omitted because their standard deviation with one or both of their neighboring means was greater than 0.7 mmol mol⁻¹ for a total rejection rate to 3% (3/94). Mn/Ca ratios were analyzed to test for authigenic contamination and all accepted data points were within acceptable values.

The accepted *N. pachyderma* Mg/Ca measurements range from 1.33 to 2.07 mmol mol⁻¹. The Mg/Ca data is presented in figure 15 as open circle points. The data set is too short to reveal orbital scale trends in Mg/Ca that could be due to ENSO behavior as discussed in previous sections. However, the data set is long enough to reveal millennial scale trends. The red line represents the smoothed 5-depth running mean of the data set and the green lines represent a ± 2 -sigma of the standard deviation. The graph displays three apparent minimums in Mg/Ca. Each minimum is spaced roughly 1000 years apart at 8.6, 9.75 and 10.75 kyr. Defining each oscillation is a Mg/Ca maximum in between each minimum at 9.1, 10.3, and 11.2 kyr. The oscillations in Mg/Ca suggest that there must have been a change in water temperature because of the positive relationship of Mg incorporation into CaCO_3 with temperature.

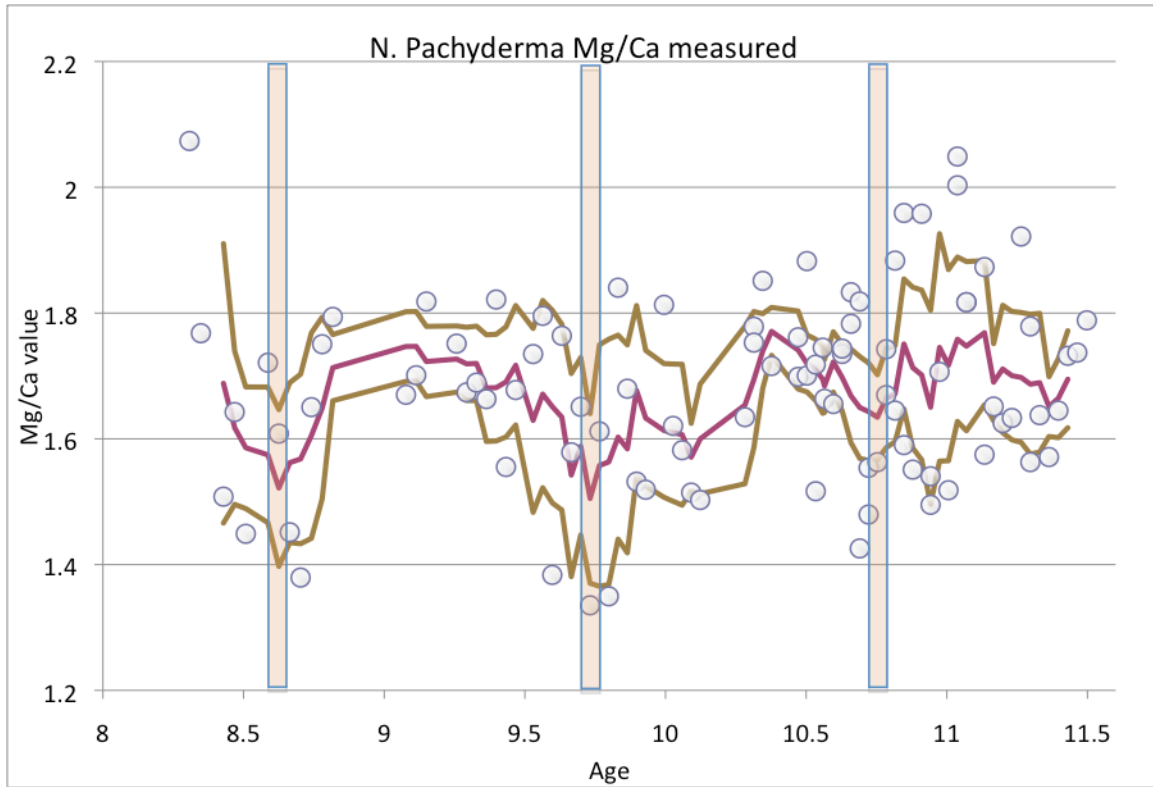


Figure 15: *N. pachyderma* Mg/Ca values during the 8.31 to 11.5 kyr interval. The open circles represent individual Mg/Ca sample points. The red line is the 5 point running mean with ± 2 sigma standard error bars in green. Shaded boxes indicate each millennial scale cooling.

The Mg/Ca data was converted to temperature using the equation of Elderfield and Ganssen (2000): $\text{Mg/Ca (mmol mol}^{-1}\text{)} = 0.5 \exp 0.10 T$. The temperatures calculated using this equation are nearly identical to the Norwegian Sea *N. pachyderma* calibrations of Nurnberg et al. as well as the cultured calibration for *N. pachyderma* of von Langen et al. (2005). The alternative equation of Kozdon et al. (2008) would give temperatures that are lower than the other noted equations. The converted *N. pachyderma* (*d.*) temperature data is presented in figure 16.

The range of temperatures recorded by *N. pachyderma* (*d.*) span 9.8 to 14.2°C. The average temperature range of the 5-depth running mean of *N. pachyderma* (*d.*) data is 12°C placing it at a depth of approximately 50m using

present day hydrographic data (IMECOCAL, G. Gaxiola). This range is consistent with the modern day depth of the DCM and the hypothesized depth of habitat for *N. pachyderma* (d.). Defined by the 5-depth running mean (black line), three oscillations are marked by troughs and peaks corresponding to the same ages as the raw Mg/Ca data. The shaded boxes mark each oscillation. The temperature data suggests that there were indeed oscillations in sea temperature recorded by *N. pachyderma* (d.) roughly every 1000 years that were felt deeper in the water than the near surface record of *G. bulloides* and appear to be concurrent with that same record.

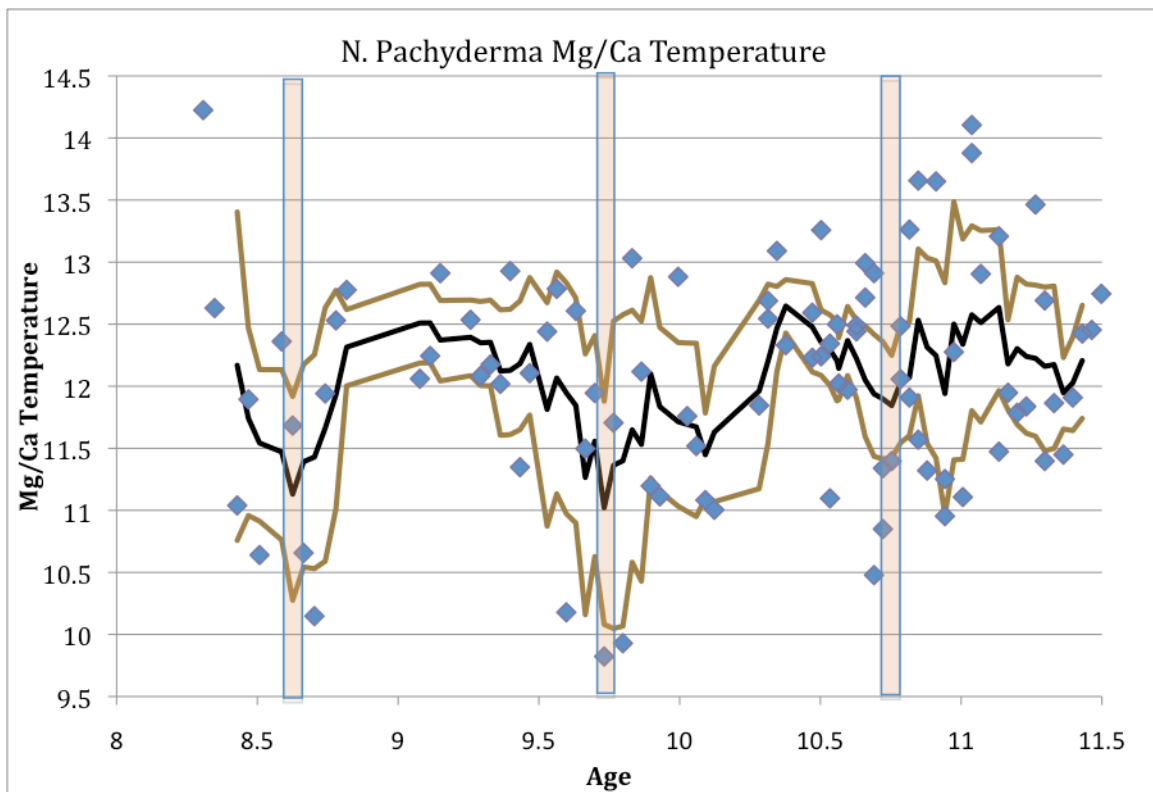


Figure 16: *N. pachyderma* (d.) Mg/Ca data converted to temperature (°C) using the equation of Elderfield and Ganssen (2000). The black line represents the 5-depth running mean and the green lines are the 2 sigma error bars. Like in figure 15, the three oscillations are visible at 8.6, 9.7 and 10.7 kyr B.P. Shaded boxes indicate millennial scale cooling.

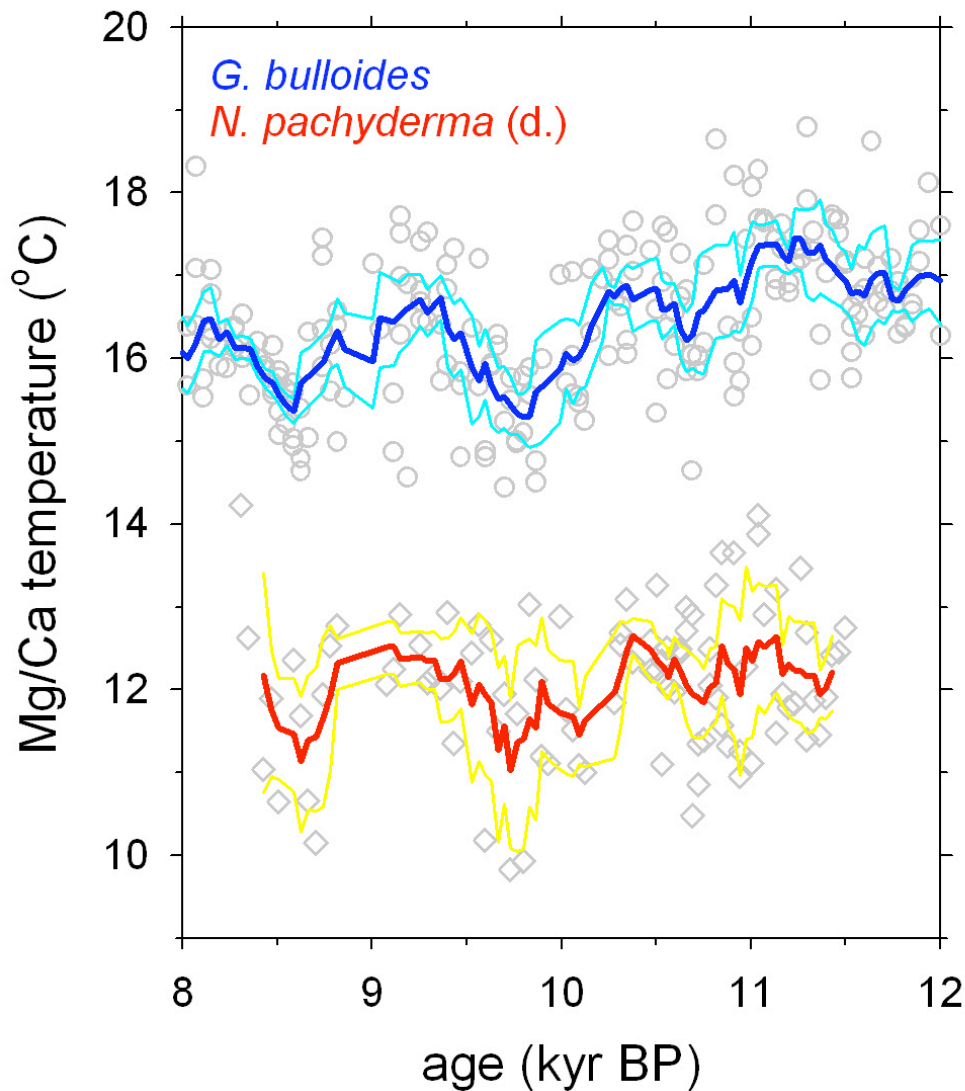


Figure 17: *G. bulloides* Mg/Ca temperature data from Marchitto et al. (2010) (open circles are individual points, blue line is 5 point mean) plotted with *N. pachyderma* (d.) temperature data (open diamonds are individual points, red line is 5 point mean). The different temperatures each species records are reflective of the vertical habitat stratification between the two, with *G. bulloides* living in warmer waters near the surface and *N. pachyderma* (d.) preferring cooler waters at depth. Additionally, the three millennial spaced oscillations recorded by *N. pachyderma* (d.) are synchronous with those recorded by *G. bulloides*. The magnitude of each oscillation is also nearly equal.

The most important assumption involved in using this multi-species approach to reconstruct changes in water column hydrography is understanding the

vertical relationship between the two species in the water column. In particular, the use of *N. pachyderma* (d.) was specifically aimed at recording temporal changes of the thermocline and associated mixed layer with little worry of vertical migration overprint due to the species' static habitat near the DCM. In the Soledad Basin, the vertical stratification between the two species is apparent in figure 17. *G. bulloides* temperatures average 16°C, 4°C warmer than the deeper dwelling *N. Pachyderma* (d.) at 12°C. This data is consistent with modern day IMECOCAL data that show a roughly 4°C difference between the surface and the DCM depth during spring. Absolute temperatures recorded by both species are slightly cooler than today. During the early to middle Holocene, temperatures were likely shifted cooler due to the orbitally-forced La Niña-like state (Marchitto et al., 2010) and thus the present day temperatures at both the surface and the DCM are warmer now.

The millennial scale oscillations in temperature recorded by *G. bulloides* and *N. pachyderma* (d.) are similar in magnitude with each other. The maximum change in temperature over the given time span occurs during the 8.6-9.7 kyr oscillation where each species records a change in temperature of about 1.5°C (*G. bulloides* range: 16.7-15.2°C; *N. pachyderma* (d.) range: 12.5-11.0°C). Similarly, each foraminifera records similar changes over the 9.7-10.7 kyr time span. The fidelity of each record shows that the changes each species recorded were synchronous with one another. The maximums and minimums of each record occur at nearly the same time and are nearly equal in duration and magnitude.

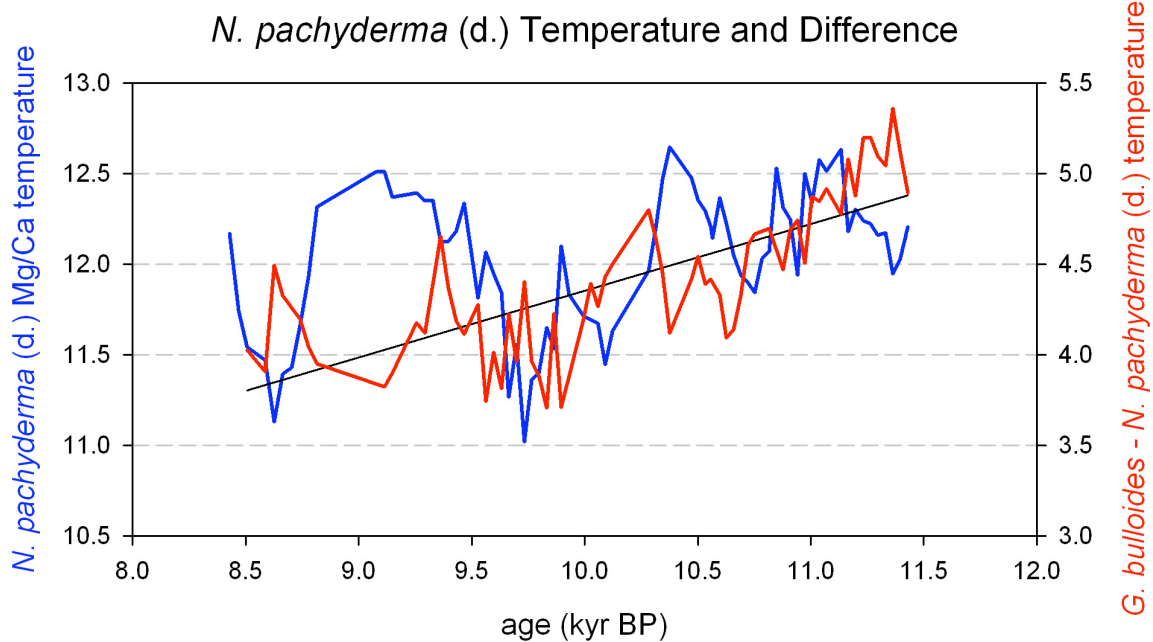


Figure 18: The *N. pachyderma* (d.) temperature record (blue) and the difference between *G. bulloides* and *N. pachyderma* (d.) temperature (red). The difference does not show large changes that coincide with the millennial-scale temperature oscillations, indicating that the species were seeing constant similar sized changes with respect to each other. This is consistent with ENSO forcing at the millennial (solar) timescale. The longer-term trend (black line) could be related to orbital forcing.

Using the 5-depth running means of each record, the *G. bulloides* temperature data was differenced with the *N. pachyderma* (d.) temperature data to observe how the two records changed with respect to each other. The difference between both records remains fairly constant with time at the millennial time scale (figure18). Small variations of .5°C exist, however, this noise is expected as both records are fairly noisy themselves, thus differencing the two is expected to contain some variability. It is interesting to note that during periods of warming events (blue line) the variability in the difference between the two species (red line) appears to be decreased, and during subsequent coolings the variability is increased. Modern

temperature profiles from the Soledad Basin show that during warm years the upper 50m of the water column becomes more thermally constant than it is during cold periods. During the peak of the strong El Niño of 2007-2008, the upper 20-30 meters of the water column became nearly uniform in temperature. Due to the very shallow nature of the thermocline at this time, the decrease in temperature with depth down to 50 meters was not as rapid as it would be in a La Niña year leaving the upper water column more thermally constant than during La Niña (cooling) events (IMECOCAL data, G. Gaxiola). This decrease in variability between the two species during warming events and the subsequent increased variance during cooling events further supports the observation of each species vertical habitat and also supports the observation that the changes in temperature they record are a result of ENSO thermocline dynamics. However, additional replicates will be required to determine if this observation is robust.

There appears to also be a long-term trend (black line) in the *G. bulloides* – *N. pachyderma* difference data. Over the 3kyr interval, there is an average 1°C change in the magnitude of the difference between each species. At 11.4 kyr the difference in temperature between the two is around 5°C with a peak at 5.2°C however, by 8.3kyr the change in temperature between the two species averages 4.2°C and ranging as low as 3.8°C. While it is too short of a record to deduce an orbital-scale pattern with any confidence, it is plausible to hypothesize that this trend is reflective of a different response of the two species to orbital forcing. Theory suggests that both species should have recorded cooling due to the orbitally forced La Niña like conditions experienced in this region during the early to middle

Holocene (see section 2.2 and 2.3 for references and discussion). *G. bulloides*, which is a springtime surface dweller, may have been additionally influenced by decreasing spring insolation during the mid-Holocene, resulting in a slow decrease of the difference with *N. pachyderma* (*d.*).

The new *N. pachyderma* (*d.*) data also correlates well to the cosmogenic nuclide data shown by Marchitto et al. 2010 (figure 19). The minimums in the *N. pachyderma* (*d.*) Mg/Ca record, concordant with the *G. bulloides* data, are synchronous with the minimums in ^{10}Be and ^{14}C indicating a stronger solar forcing and more La Niña like state. Unfortunately the Asian monsoon records share only a small overlap with the *N. pachyderma* (*d.*) data. The North Atlantic IRD data also measures up well to the new data set and like the monsoon and *G. bulloides* Mg/Ca, the *N. pachyderma* (*d.*) records becomes offset from the solar and IRD records around the 8.2 ka event as discussed in section 2.3.

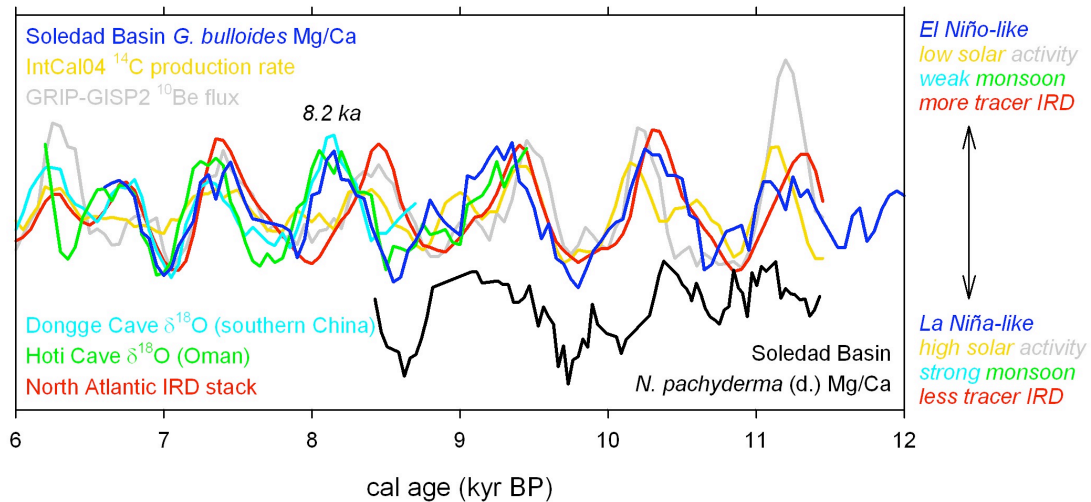


Figure 19: New *N. pachyderma* (*d.*) data (black line) plotted against *G. bulloides* (blue), solar proxies (^{10}Be -grey, ^{14}C yellow), and ENSO proxies (North Atlantic IRD-red, monsoon-light blue and green). Each record is plotted on its own age model. Minimums in the cosmogenic nuclides (high solar activity) correspond to minimums in the *N. pachyderma* (*d.*) and *G. bulloides* temperatures consistent with

the ocean dynamical thermostat solar forcing and a La Niña like state. These conditions coincided with strong Asian monsoons and less drift ice in the North Atlantic.

CHAPTER 6: CONCLUSIONS

ENSO is responsible for large-scale interannual climate variability on a global scale. However, little is known about how the ENSO system influenced climate in the past outside of the instrumental records, and for this, its role in GCM simulations and other paleoclimate studies has been limited. Using the Zebiak-Cane model, a system designed specifically to simulate ENSO, researchers have identified an “ocean dynamical thermostat”. This mechanism states that with a positive (or negative) solar forcing the equatorial Pacific responds with a cooling (or warming). The coolings and warming can be attributed to a preferred tendency of ENSO to one state. That is, for a positive solar forcing, SST gradients are increased resulting in a La Niña like response in the EP upwelling cooler waters to offset the increased temperatures. Studies using the Zebiak Cane model attempting to simulate the ocean dynamical thermostat response of ENSO during the Holocene found that ENSO was characterized millennial scale changes thought this time.

However, until just recently, this response was yet to be clearly identified in the paleoclimate record until Marchitto et al. 2010 found that the planktonic foraminifera *G. bulloides* recorded 5 millennial scale oscillations in SST between 7 and 11.5 kyr B.P in a core from the Soledad Basin, Baja California. This SST record coincided with records of cosmogenic nuclide production proxies, further supporting the Zebiak-Cane model hypothesis that during the Holocene, ENSO was forced at least in part by solar activity. *G. bulloides* prefers a habitat in the upper mixed layer. The modern day SST anomalies pattern at the Soledad Basin are highly coupled to ENSO because ENSO controls the thermocline variability in this region.

While there is almost no modern SST relation to local upwelling, the *G. bulloides* record should be tested for the possibility that during the early to middle Holocene, upwelling played a much stronger role in controlling SST variability. To test the hypothesis that the 5 millennial scale oscillations recorded by *G. bulloides* are in fact due to a solar forcing of ENSO, I used the sub-surface dwelling planktonic foraminifera *N. pachyderma (d.)*. This foraminifera lives deeper down in the water column than *G. bulloides* occupying a relatively stable depth of habitat near the DCM, with little vertical migration. If the 5 oscillations in the *G. bulloides* record are in fact due to thermocline variability related to ENSO, then the *N. pachyderma (d.)* record should also show oscillations that are both similar in magnitude and concurrent with the *G. bulloides* record.

I have identified three synchronous millennial scale oscillations between 8.31 and 11.5 kyr (the record is not long enough to capture the 2 most recent events). Each oscillation is nearly identical in magnitude to *G. bulloides* with variability in each species ranging as high as 1.5°C over the 8.6 to 9.7 kyr oscillation. The two records show the vertical habitat stratification relationship in the water column with near-equal changes in temperature through time. The difference in the 5-depth running means of each data set show no difference between warm and cool episodes at millennial time scales, indicating that both the surface and subsurface were seeing the same magnitude changes in temperature at the same time. The new *N. pachyderma (d.)* data set positively correlates to the cosmogenic nuclide proxies and IRD in the same way the *G. bulloides* data does. The use of this multi-foraminifera method to evaluate changes in thermocline hydrography has shown

that the millennial scale oscillations in both species records are most likely due to an ENSO forcing of the thermocline which was hypothetically driven by a solar forcing on the equatorial Pacific.

Future work will involve finishing the *N. pachyderma* (*d.*) record to span the 5 oscillations as *G. bulloides*. Continued work on paleo-ENSO will only continue to further our knowledge as to the role it has played in paleoclimate scenarios. If future results continue to show that ENSO may be susceptible to solar forcing then GCM simulations need to take this into account. Society relies heavily on GCM predictions because they are the strongest simulations for the future available. With ENSO being a leading cause of global scale climate variance at interannual timescales, understanding how ENSO may change due to parameters that can be instrumentally monitored (i.e. solar activity, global warming, etc) will better society's ability to prepare and adapt for future ENSO events. It is the scientists purpose to not just conduct the science, but to educate those whose fund it. The impact of understanding past and present ENSO can have an immediate impact for communities and ourselves.

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Luthi et al 2008

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